Groundwater for Sustainable Development 6 (2018) 87–92

Contents lists available at ScienceDirect

Groundwater for Sustainable Development

journal homepage: www.elsevier.com/locate/gsd

Desalination of deep groundwater aquifers for freshwater supplies – Challenges and strategies

ARTICLE INFO

Keywords:
Groundwater
Desalination
Climate change
Strategies and management
Governance water reuse

ABSTRACT

Groundwater depletion is a common problem in most of the countries across the world. This is caused by excess population growth, improved living standards, and climate change issues. Many regions across the world are accessing deep groundwater sources for managing water supply demands. This research article presents issues related to accessing deep groundwater sources in regions like California, USA. Potential environmental, technological and governance related groundwater management issues associated with desalination of deep groundwater reserves are discussed briefly. A concise discussion on global water supply issues and potential strategies to overcome the present barriers are presented for both developed and developing countries.

1. Introduction

About 98% of global freshwater sources are stored underground which is used by approximately 2.5 billion people worldwide for their daily needs (Margat, 2008, Margat and van der Gun, 2013). The groundwater withdrawal rates are increasing by 1–3% annually across the world due to population growth and higher living standards. This increased level of abstraction coupled with groundwater pollution has caused many issues for groundwater-dependent ecosystems. Climate change and its variability, on the other hand, affects the groundwater recharge rates (Taylor et al., 2013). This situation has triggered many communities to access deep groundwater sources. These sources are often saline in nature and may cause additional environmental concerns. Therefore, it is crucial to develop and implement effective management practices to protect and properly utilize this rather finite source. Management practices may include both technical and non-technical approaches. Understanding the importance of groundwater governance and it proper implementation to efficient management practices could enhance the accessibility of groundwater resources for long-term sustainability.

The purpose of this article is two-fold. First, a discussion of the global groundwater depletion problems is presented. Next, a few case studies detailing issues and or management practices related to sustainable groundwater governance and its implementation in developed and developing countries are presented.

2. Global groundwater depletion problem

Groundwater depletion is a local, regional and global problem and increasing withdrawal of groundwater for domestic water supplies and agricultural uses has become a major challenge for many local water management agencies. Despite the critical importance of the groundwater source for sustainable development, insufficient management attention is given to these sources in comparison with surface water sources (Famiglietti, 2014). Groundwater sources are often poorly monitored and managed and sometimes they do not receive any attention in some developing countries.

Groundwater resources are finite and deplete with continued withdrawals (“overdraft”), a phenomenon often termed as “water mining” for our increasing demands. For example, in USA, groundwater withdrawal rates more than doubled in the period from 1965 to 1995 to supply domestic consumption, with substantially larger groundwater abstraction occurring to support industry such as mining and irrigated crops (Glennon, 2002; Doody et al., 2017). Recently, 43% of total global irrigation water was extracted from groundwater sources, with America and Asia extracting 48% and 45% respectively (Siebert et al., 2010). Furthermore, approximately 25% of the world's population depend on groundwater pumping for drinking water, many of these in semi-arid and arid zones (Glennon, 2002). Some recent trends of groundwater aquifers depletion rates are shown in Fig. 1. It is evident that some level of groundwater depletion is persistent across the world in major groundwater reserves which has caused water stress issues in these regions (Wada et al., 2010).

3. Groundwater depletion trends in the USA

Fig. 2 shows the regions in the USA where groundwater depletion is highly pronounced. In some regions, though they were originally water-rich, the depletion rates are very high (Konikow, 2013). This is usually associated with increased withdrawals for irrigation as in the case of Mississippi. In some cases, it is compounded by the water needs due to excessive population growth, for example the water crisis in Central valley of California.

As the quantity declines in many groundwater reserves, the quality of the source becomes unsuitable for many purposes due to other undesired

https://doi.org/10.1016/j.gsd.2017.11.002
Received 23 August 2017; Received in revised form 18 November 2017; Accepted 21 November 2017
Available online 23 November 2017
2352-801X/ © 2017 Published by Elsevier B.V.

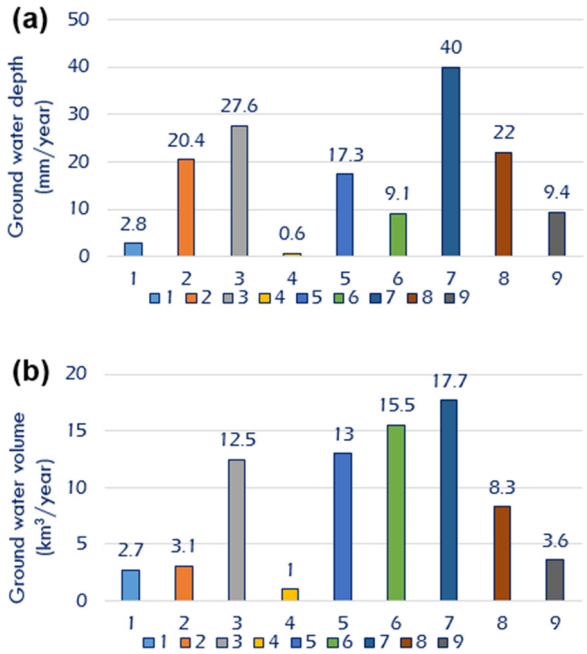

Fig. 1. Groundwater depletion in major aquifers around the world (Famiglietti, 2014); (a) groundwater depth in mm/yr and (b) groundwater volume in km^3/yr. 1. Northwest Sahara Algeria, Libya, Tunisia (2003–2013); 2. California Central Valley USA (2003–2010); 3. High Plains (Ogallala) USA (2003–2013); 4. Guarani Argentina, Brazil, Paraguay, Uruguay (2003–2009); 5. Northern Middle East Iran, Iraq, Syria, Turkey (2003–2009); 6. Arabian Iraq, Jordan, Oman, Qatar, Saudi Arabia, UAE, Yemen (2003–2013); 7. Northwestern India India, Pakistan (2002–2008); 8. North China Plain China (2003–2010) and 9. Canning Basin Australia (2003–2013).

groundwater chemistry that could take place due to soil and water contact. In many parts of the world, ground water is not suitable for direct consumption. They are impaired either due to naturally occurring hazardous substances such as uranium, fluoride and arsenic (Yarlagadda et al., 2011). In some cases, the impairment is caused by illicit discharges by industrial sectors. Often, these ground waters also contain high dissolved solids leading to their categorization as brackish waters. Traditional treatment techniques are not adequate to remove the dissolved solids. For instance, two-thirds of the continental United States including New Mexico has large volumes of saline water sources. The total volume of ground water in aquifers in New Mexico is estimated to be 20 billion acre-feet, however, 75% of the groundwater is too saline (10,000–35,000 ppm)for most uses and the remaining 25% of the ground water contains dissolved concentrations of lower than 2000 mg/L.

4. California as a case study

Excess withdrawal of easily accessible groundwater reserves create number of challenges in the form of water quality impairment caused by induced leakage from the land surface, confining layers or adjacent aquifers containing saline or contaminated water (Konikow and Kendy, 2005). For coastal regions, this causes seawater intrusion into ground water aquifers. Many large cities in the coastal areas currently experience this problem. This situation stems interest for exploring alternative water sources for freshwater supplies. In a recent study, Kang and Jackson (2016) presented deep groundwater sources as new untapped potential water sources for drought-stricken California. The deep groundwater source may be attractive for the local administrators to meet the increasing demands for water supplies in the region. This finding ignites interest in several sectors including academia, industry and governing agencies and appears to provide exciting opportunities for research and development. While this is true, three major issues related to accessing the deep groundwater sources can be listed as 1) environmental resource depletion and associated vulnerabilities, 2) Desalination and water reuse energy-water nexus and process feasibility and 3) new strategies and inclusive governance for new groundwater resource management.

4.1. Environmental resource evaluation

Between 1960 and 2000, the population in the central valley doubled reaching 6.5 million people in 2005 and the future growth is projected to continue (Anon, 2009). The central valley of California groundwater source has already depleted by 31.0 ± 3.0 km^3 between the drought period of 2006 and 2010 due to excessive irrigation usage (Scanlon et al., 2012). Continued and extensive use of groundwater and related environmental harm (i.e. water-level drawdown, aquifer mining and pollution, saltwater intrusion, stream base-flow reduction, and land-surface subsidence) implies the difficulty of efficiently and equitably defining, allocating, and protecting rights to this new water resource (Koundouri, 2004). Impacts of introducing new water sources to the surface on the receiving water bodies and the coastal seawater rises should also be considered as recent studies report the contribution of groundwater discharges to global sea-level rise increased from 0.02 (± 0.004) mm yr^{-1} in 1900 to 0.27 (± 0.04) mm yr^{-1} in 2000 (Wada et al., 2016).

4.2. Desalination and water reuse technology assessment

Although salinity of the deep groundwater sources is lower than the seawater, the energy requirements to treat these waters can pose a challenge to local electric grids (Gude, 2015, 2016, 2017). Variable salinity feed is also possible with continued withdrawals in this region. The challenge of providing reliable potable water systems includes inventions in the design of flexible desalination systems to take better advantage of the capital

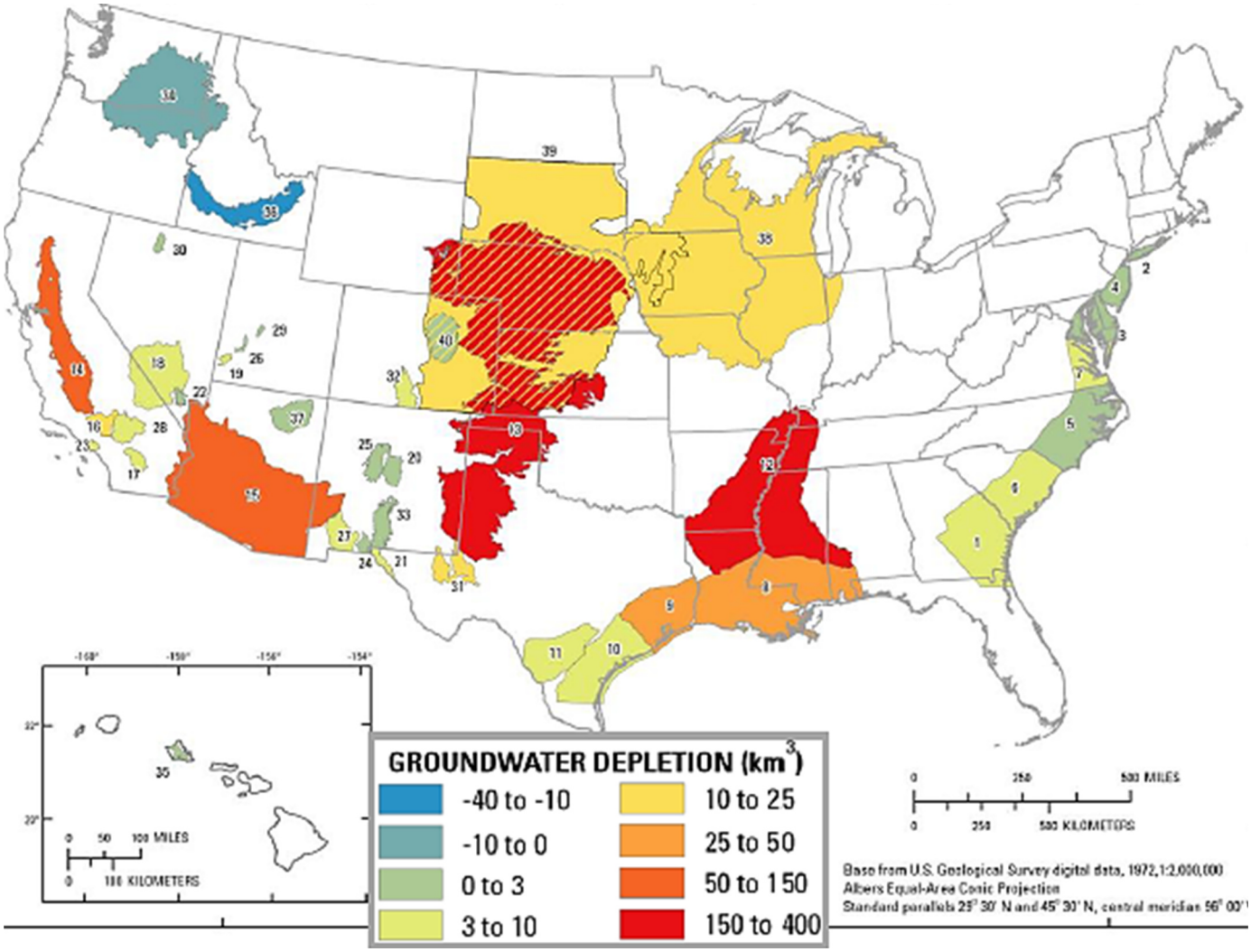

Fig. 2. Groundwater depletion in the United States between 1900 and 2008 (Konikow, 2013).

equipment investments in these coastal regions (Gude, 2011). In view of the aforementioned potential vulnerabilities and energy-water nexus issues, blending both the seawater and groundwater sources for desalination application appears to mitigate the subsidence of land surface and provide recharge times for the groundwater naturally from precipitation and other discharges. As deep groundwater becomes the new potable water supply source, treated wastewaters as well as produced waters from oil and gas operations become part of the integrated water management scheme for these drought-stricken areas. Novel desalination technologies that can utilize high salinity and high hardness containing produced waters as feed are yet be developed to address water scarcity most economically (Meng et al., 2016).

Alternatively more aggravated water reuse option could be considered in these regions prior to considering desalination option (Gude et al., 2010). Ten percent of the total available freshwater, or 3.5 million km^3, is consumed around the world. Of this amount, about 330 km^3 are generated globally as municipal wastewater (NRC, 2012). For example, of the 32 billion gallons—or 121 million cubic meters (m^3)—of municipal wastewater discharged nationwide in the United States each day, approximately 45.5 million m^3 are discharged to an ocean or estuary—an amount equivalent to 6% of total water use in the United States. Reusing this water would directly augment the nation's total water supply. However, water reuse may not be an affordable alternative in all scenarios. Readers are referred to recent contributions on desalination and water reuse topics for detailed list of technological and management alternatives (Gude, 2015, 2016, 2017). Desalination processes are mainly classified into membrane and thermal processes. Membrane processes are also commonly used for water reuse applications around the world. Desalination processes leave a concentrated stream called “brine” which is a major environmental concern. A comparison of possible reuse, recovery rates and representative costs for desalination, water reuse and concentrate management technologies are shown in Fig. 3. It can be noted that water treatment costs increase with complexity of the process and the end water quality. For recycling and reuse options, zero liquid discharge options are being developed which are energy- and cost-intensive at present.

4.3. New strategies and inclusive governances

Understanding the deterioration of global groundwater supplies will be the first step towards developing a sustainable framework for groundwater resilience. Most of the current water laws and policies in the developed world were developed in times, when the tight interconnections between surface water and groundwater were poorly appreciated (Famiglietti, 2014). This suggests that groundwater well governance requires a new paradigm shift to protect the environmental resources, their operations and management (Conrad et al., 2016; de Chaisemartin et al., 2017). It

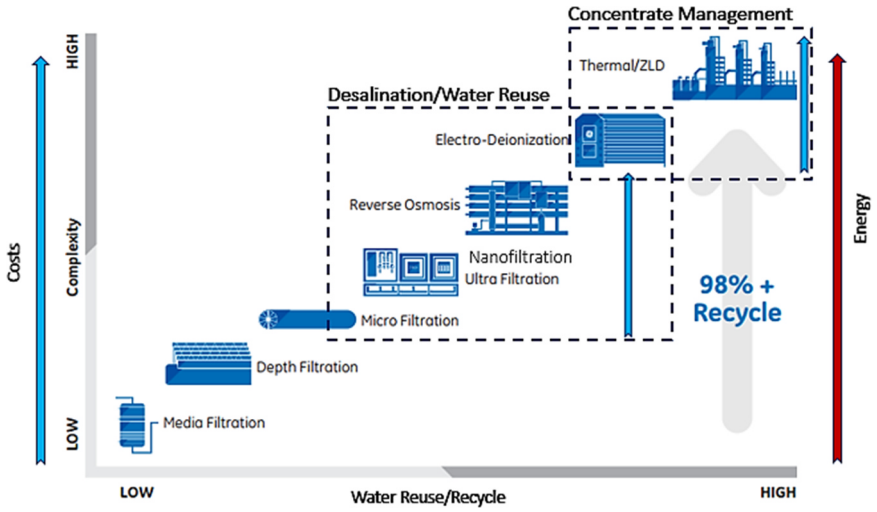

Fig. 3. Desalination and water treatment options and water reuse and concentrate management options and cost-recovery/reuse relationships (modified after GE, 2015).

may be possible to exploit current wells to access deeper aquifers or new well development may be required in some cases. Regardless, this leads to a need for new groundwater governance among the groundwater sustainability agencies (GSA). Well-coordinated approaches across various agencies are crucial for sustainable development of this new water resource, given the diverse portfolio of groundwater management across the state and for similar situations around the world (NRC, 2012).

For example, the state of California has introduced a sustainable groundwater management act in 2014 with the aim of managing groundwater sources with consideration of long-term sustainability and reliability along with enhancement of economic, social, and environmental benefits (Kiparsky et al., 2016). This act also initiated the establishment of groundwater sustainability agencies by local groundwater agencies and participating stakeholders (groundwater and surface water users, representatives of cities, agencies, water companies and environmental scientists and planners). GSAs should be developed based on the following criteria: scale, human capacity, funding, authority, independence, participation, representation, accountability, and transparency. This approach is expected to accomplish a highly efficient governance of the groundwater management in medium- and high-priority groundwater basins across the state. As of January 2017, 154 GSA notices have been submitted for approval and 88 basins have already established approved GSAs across 30 counties with 57 high- or medium-priority basins and 31 low- or very-low priority basins. Proper implementation of governance includes institutional design (structures and rules for management), governance (processes and mechanisms and organizations that help develop public policies, laws and regulations along with administrative and organizational structures), and management (specific actions to determine use and protection of groundwater resources).

5. Groundwater management in developing countries

Groundwater governance and management in developing countries is quite complex. Many developing countries rely heavily on agriculture for their food self-sufficiency and to sustain economies. In this context, exploitation or even overexploitation of groundwater sources is a common and inevitable practice. The following paragraphs discuss some of the novel practices developed to sustain groundwater governance and management in developing countries.

In western part of India (State of Gujarat), when the government efforts failed in controlling the groundwater overexploitation, local communities have taken several initiatives inspired by local religious leaders (Van Steenbergen and Shah, 2003). These initiatives include rain harvesting during monsoon season and grassroots movement. These efforts were soon adopted by other neighboring communities leading to state level recognition by the authorities. This is an example for achieving groundwater governance with public-private partnership and cooperation between government agencies.

Similar to India, China is also dependent on groundwater sources for food supplies and to foster agriculture-based economy. This country also faces issues related to overexploitation of groundwater sources. In contrast to India, China has a centralized mechanism in which each village has a local government employed (paid by local taxes) representative who is responsible for setting the water use fee and planning and implementation of irrigation practices (Shah, 2005).

Considering the long-term and complex groundwater management issues faced at local, regional, national and international levels, a global framework for action called “Groundwater Governance Project” was developed UNESCO-IHP recently (Groundwater Governance Project 2016a, 2016b, 2016c; de Chaisemartin et al., 2017). This project developed a shared global vision for the year 2030 which includes the following working principles:

a) Groundwater should not be managed in isolation, but conjunctively as appropriate with other water sources to improve water security and assure ecosystem health.
b) Groundwater quality and other resources should be co-managed.
c) Vertical integration (central and local) between national and local level participation in the elaboration and implementation of groundwater management and protection plans should be considered as much as possible.
d) Coordination should be established with other sectors such as agriculture, energy, health, urban and industrial developments and the environment.

Several other options can be considered to groundwater governance programs to be effective (see Fig. 4). These options are: education and

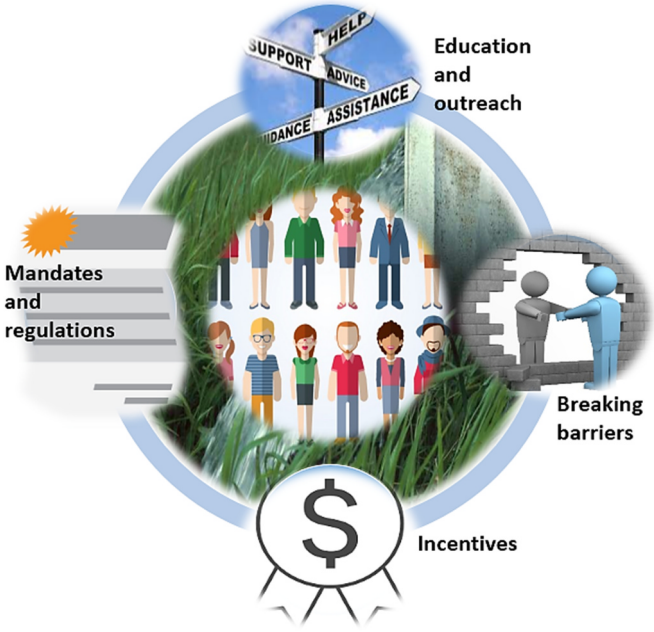

Fig. 4. Strategies for sustainable groundwater management.

outreach, incentives, removing barriers, and mandates and regulations (GE, 2015; Gude, 2017). Education and Outreach may include programs that promote certification programs and recognition awards. Programs to disseminate the scientific information and general benefits and essential facts related to groundwater protection and sustainable resource management by education and outreach efforts. Educating the users on water withdrawal trends, consumption, discharge and reuse data is critical to governance implementation. An incentive program including direct subsidies, reductions in payments to the government, payments for water reuse, adjusting pricing mechanisms, regulatory relief for recycled water users, government procurement of water recycling/reuse equipment and structuring of water rights to reduce the use of potable water can be considered. Regulatory reliefs may include modification of local regulations depending on the application especially in terms of water quality standards, revising laws, and permitting requirements. Creating mandatory requirements should consider utility planning and management to develop plans for recycled water, restricting potable water to human or food-related uses, and requiring the use of recycled water for agriculture and other non-potable uses and requiring water recovery systems.

6. Conclusions

Groundwater governance and its sustainable implementation depends on various factors, including availability of accurate information, financial support, policy framing and implementation. However, another key component of groundwater management is being able to forecast groundwater levels with a high degree of accuracy. The precise prediction of groundwater levels can help policymakers resolve the best approach to groundwater management problems. This article discussed issues related to groundwater depletion in both developed and developing countries and provided recommendations for proper implementation of groundwater governance and its management.

References

de Chaisemartin, M., et al., 2017. Addressing the groundwater governance challenge. In: Karar, E. (Ed.), Freshwater Governance for the 21st Century. Global Issues in Water Policy 6. Springer, Cham, pp. 205–227.

Conrad, E., Martinez, J., Moran, T., DuPraw, M., Ceppos, D., Blomquist, W., December 2016. To Consolidate or Coordinate? Status of the Formation of Groundwater Sustainability Agencies in California.

Doody, T.M., Barron, O.V., Dowsley, K., Emelyanova, I., Fawcett, J., Overton, I.C., Warren, G., 2017. Continental mapping of groundwater dependent ecosystems: a methodological framework to integrate diverse data and expert opinion. J. Hydrol.: Reg. Stud. 10, 61–81.

Famiglietti, J.S., 2014. The global groundwater crisis. Nat. Clim. Change 4 (11), 945–948.

Faunt, C.C., 2009. Groundwater Availability of the Central Valley Aquifer, California. US Geological Survey, Reston, VA (Professional Paper 1766).

GE, 2015. Addressing Water Scarcity through Recycling Andreuse: A Menu for Policymakers. White paper by Jon Freedman and Colin Enssle.

Glennon, R., 2002. Water Follies: Groundwater Pumping and the Fate of America's Fresh Waters. Island Press, Washington.

Groundwater Governance Project, 2016a. Global Diagnostic on Groundwater Governance. Groundwater Governance – A Global Framework for Action, GEF, UNESCO-IHP, FAO, World Bank and IAH. ⟨http://www.groundwatergovernance.org⟩.

Groundwater Governance Project, 2016b. Groundwater Governance, A Call for Action: A Shared Global Vision for 2030. Groundwater Governance – A Global Framework for Action, GEF, UNESCO-IHP, FAO, World Bank and IAH. ⟨http://www.groundwatergovernance.org⟩.

Groundwater Governance Project, 2016c. Global Framework for Action to Achieve the Vision on Groundwater Governance. Groundwater Governance – A Global Framework for Action, GEF, UNESCO-IHP, FAO, World Bank and IAH. ⟨http://www.groundwatergovernance.org⟩.

Gude, V.G., Nirmalakhandan, N., Deng, S., 2010. Renewable and sustainable approaches for desalination. Renew. Sustain. En. Rev. 14 (9), 2641–2654.

Gude, V.G., 2011. Energy consumption and recovery in reverse osmosis. Desalination W. Treat. 36 (1–3), 239–260.

Gude, V.G., 2015. Energy storage for desalination processes powered by renewable energy and waste heat sources. Appl. Energy 137, 877–898.

Gude, V.G., 2016. Desalination and sustainability – an appraisal and current perspective. Water Res. 89, 87–106.

Gude, V.G., 2017. Desalination and water reuse to address global water scarcity. Rev. Environ. Sci. Bio/Technol. 16 (4), 591–609.

Kang, M., Jackson, R.B., 2016. Salinity of deep groundwater in California: Water quantity, quality, and protection. Proc. Natl. Acad. Sci. USA 201600400.

Kiparsky, M., Owen, D., Green Nylen, N., Doremus, H., Christian-Smith, J., Cosens, B., et al., 2016. Designing Effective Groundwater Sustainability Agencies: Criteria for Evaluation of Local Governance Options.

Konikow L.F., 2013. Groundwater depletion in the United States (1900–2008). U.S. Geological Survey Scientific Investigations Report 2013–5079, 63 p. (Available only online). ⟨http://pubs.usgs.gov/sir/2013/5079⟩.
Konikow, L.F., Kendy, E., 2005. Groundwater depletion: a global problem. Hydrogeol. J. 13 (1), 317–320.
Koundouri, P., 2004. Current issues in the economics of groundwater resource management. J. Econ. Surv. 18 (5), 703–740.
Margat, J., 2008. Exploitations et utilisations des eaux souterraines dans le monde. Coédition: UNESCO et BRGM, 52p.
Margat, J., Van der Gun, J., 2013. Groundwater Around the World: A Geographic Synopsis. CRC Press, EH Leiden, The Netherlands.
Meng, M., Chen, M., Sanders, K.T., 2016. Evaluating the feasibility of using produced water from oil and natural gas production to address water scarcity in California's Central Valley. Sustainability 8 (12), 1318.
NRC, National Research Council, 2012. Water Reuse: Potential For Expanding The Nation's Water Supply Through Reuse Of Municipal Wastewater. National Academies Press, Washington, D.C., USA.
Scanlon, B.R., Longuevergne, L., Long, D., 2012. Ground referencing GRACE satellite estimates of groundwater storage changes in the California Central Valley, USA. Water Resour. Res. 48 (4).
Shah, T., 2005. The new institutional economics of India's water policy. Afr. Water Laws: Plur. Legis. Framew. Rural Water Manag. Afr. 26–28.
Siebert, S., Burke, J., Faures, J.M., Frenken, K., Hoogeveen, J., Döll, P., Portman, F.T., 2010. Groundwater use for irrigation – a global inventory? Hydrol. Earth Syst. Sci. 14 (10), 1863–1880.
Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., et al., 2013. Ground water and climate change. Nat. Clim. Change 3 (4), 322–329.
Van Steenbergen, F., Shah, T., 2003. Rules rather than rights: self-regulation in intensively used groundwater systems. Intensive Use Groundw.: Chall. Oppor. 241–256.
Wada, Y., van Beek, L.P., van Kempen, C.M., Reckman, J.W., Vasak, S., Bierkens, M.F., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37 (20).
Wada, Y., Lo, M.H., Yeh, P.J.F., Reager, J.T., Famiglietti, J.S., Wu, R.J., Tseng, Y.H., 2016. Fate of water pumped from underground and contributions to sea-level rise. Nat. Clim. Change 6, 777–780.
Yarlagadda, S., Gude, V.G., Camacho, L.M., Pinappu, S., Deng, S., 2011. Potable water recovery from As, U, and F contaminated ground waters by direct contact membrane distillation process. J. Hazard. Mater. 192 (3), 1388–1394.

Veera Gnaneswar Gude
Department of Civil and Environmental Engineering, Mississippi State University, Mississippi State, MS 39762, USA
E-mail addresses: gudevg@gmail.com, gude@cee.msstate.edu.